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MELBOURNE, VICTORIA

REPORT

MRL-R-847

RESIDUAL STRESSES IN SWAGE-AUTOFRETTAGED

THICK-WALLED CYLINDERS

Graham Clark

Approved for public release

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FEBRUARY 1982

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DOCUMENT CONTROL DATA SHEET

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-R-847	AR-002-757	Unclassified

TITLE

RESIDUAL STRESSES IN SWAGE-AUTOFRETTAGED THICK-WALLED CYLINDERS

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REPORT DATE	TASK NO.	SPONSOR
February, 1982	DST 77/069	DSTO

CLASSIFICATION/LIMITATION REVIEW DATE	CLASSIFICATION/RELEASE AUTHORITY
	Superintendent, MRL Metallurgy Division

SECONDARY DISTRIBUTION

Approved for Public Release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Autofrettage	Pressure Vessels	Residual Stress Distribution
Gun Barrels	Cylinders	
Crack Propagation	Swaging	
	Thermal Crazing	

COSATI GROUPS	1906	1308	2012

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C O N T E N T S

LIST OF SYMBOLS

a	Bore radius
b	External radius of barrel
e_b	Bore strain (radial)
e_{sw}	Radial strain of swage
E	Young's modulus of barrel material
E_{sw}	Young's modulus of swage material
E_s	Bauschinger energy parameter
k	Barrel wall ratio (= b/a)
n	Monotonic yield ratio (= r^*/a)
P	Bore pressure
P_1, P_2, P_3	Effective radial pressures transmitted across interfaces in barrel wall
r	Radius to element in barrel wall
r^*	Radius of monotonic yield zone, at autofrettage pressure
Y	0.2% Offset proof stress
Y^*	Modified proof stress
β	Bauschinger effect parameter
ε_c	Bauschinger strain
ε_b	Plastic strain in tension test
ρ^*	Radius of reversed plastic zone
ν	Poisson's ratio
σ_h	Tangential stress
σ_r	Radial stress
σ_L	Longitudinal stress in swage
σ_z	Longitudinal stress in barrel

RESIDUAL STRESSES IN SWAGE-AUTOFRETTAGED

THICK-WALLED CYLINDERS

1. INTRODUCTION

1.1 Autofrettage Residual Stresses

The use of shrunk-on hoops or bands in gun barrel construction dates back to the earliest manufacture of guns [1], and apart from being a means of producing a hollow cylinder, or "barrel", from strips of wrought iron, this technique almost certainly improved the strength of the finished tube by introducing residual compressive hoop stresses at the bore. Similar procedures, involving hoops and thick or thin jackets, were the sole means of strengthening both cast and forged barrels until the introduction, towards the end of the 19th century, of wire-wrapped barrel construction, in which compression was applied to the bore region by adjusting the tension used in wrapping a steel wire or ribbon around the tube.

Further improvements, on the basis of increased barrel strength-to-weight ratio and reduced costs, were obtained by the use of the autofrettage technique [2], which involves producing permanent deformation of the bore by hydraulic pressurization or by pushing an oversize mandrel or swage (see Fig. 1) through the forging. After the autofrettage pressure is removed, the elastically deformed outer layers of the barrel attempt to return to their original diameter, and meet resistance from the permanently-deformed bore material. The resulting residual hoop stresses, which are compressive at the bore and tensile at the exterior wall, effectively increase the elastic strength of the cylinder, in that the severe hoop tension produced at the bore by the firing pressure is opposed by the residual compression; higher firing pressures are therefore attainable without the risk of permanent barrel distortion in service.

Increased barrel strength-to-weight ratio is still the primary reason for the continued use of hydraulic and swage autofrettage. However, a further benefit associated with the growth of bore fatigue cracks is assuming greater importance. A network of thermal craze cracks forms on the bore

surface in the first few rounds of operation, and the effect of bore residual compressive stress is to retard the growth of fatigue cracks which develop from the crazes, and then grow into the wall under the influence of cyclic firing stresses. While gun barrels had short wear lives and were manufactured from low-strength steels with high resistance to fracture, this effect had little significance. However, the recent use of effective anti-wear additives in propellants has produced marked increases in wear lives, so that greater use of high-strength steels with inherently low resistance to fracture has led to a situation in which catastrophic failure of some barrels by fracture can only be avoided by the imposition of a fatigue safe life. The determination of a suitable condemnation criterion usually relies on firing a number of barrels to destruction, and there is considerable interest in supplementing and eventually replacing this technique with life predictions based on a combination of experience and theoretical analysis. Models used in life prediction rely heavily on estimating the crack tip stress intensity which controls fatigue crack growth, and the stress-intensity component produced by autofrettage residual stresses is crucial, in that the presence of these stresses is known to extend the lives of cylindrical pressure vessels by a factor of 2 to 3 [3,4] making it essential that residual stress distributions are known with sufficient accuracy for prediction purposes.

1.2 *MRL Research on Crack Growth in Residual Stress Fields*

The approach to barrel life prediction adopted at MRL has involved development of techniques for accurate determination of the basic fatigue-crack growth rate properties of gun steels [5], followed by the use of a weight-function technique [6] for the estimation of crack tip stress-intensities which may then be used to estimate fatigue crack growth rates under service conditions. Confidence in the ability of this method to predict the reduction in growth rates observed in autofrettaged gun barrels can only be acquired by direct experimental confirmation of predicted crack growth rate effects. Hence, an additional experimental research program is being undertaken, using the Australian-manufactured L1A3 76 mm gun barrel as an example for which theoretical and experimental growth rates can be compared. Sections of gun barrel have been swage-autofrettaged using different interferences between swage and bore to produce various levels of autofrettage overstrain; a control was included in which the deformation produced by the swage was entirely elastic and hence produced no residual stress. Ring specimens approximately 25 mm thick, were cut from the central part of the autofrettaged barrel sections, to minimize end effects. Fatigue crack growth rate reductions were determined using the following approaches to assess our ability to predict the effects of autofrettage residual stresses on fatigue crack growth rate:

(i) Experimental measurement of fatigue crack growth rates, and by comparison of results for different barrels, determination of the reduction in growth rates produced by various autofrettage procedures.

(ii) Experimental determination of residual stresses produced by different swage-autofrettage levels followed by a comparison with predicted residual stresses. The

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residual stress distributions are used with a weight
function analysis to predict the reduction in crack tip
stress intensity associated with autofrettage.   Using the
relationship between the crack tip stress intensity and
crack growth rates, the reduction in growth rate expected
at each crack length can then be predicted for each
autofrettage condition.

The use of barrel sectioning to provide specimens for X-ray or any
other residual stress analysis is only permissible for a limited number of
barrel forgings, (and only one or two of the variables used in autofrettage
can therefore be investigated). A technique for predicting residual stress
distributions from the material's mechanical properties and the autofrettage
conditions is clearly an essential feature of any practical life-prediction
exercise.

This report presents details of the experimental determination of
residual hoop stress in the 76 mm barrel sections described above, and
compares these stress distributions with those predicted from the swage
autofrettage conditions used in production of the barrels.

2.   PREDICTION OF RESIDUAL STRESSES AND EXPANSIONS

2.1 Assumptions

The behaviour of thick-walled cylinders under internal pressure has
been the subject of detailed discussion [e.g. 7-14] in which the influence of
factors such as end conditions and choice of a suitable yield criterion on
residual stresses and expansions has been considered.   All of these workers
found it necessary to make major assumptions about the stress distributions
and yield conditions in order to simplify the treatment of elastic-plastic and
fully plastic cylinders, but in each case solutions were based on the Lamé
equations, generalized Hooke's Law, and the equilibrium equation for a thick
walled cylinder.

The same approach is adopted here, but the need to consider specific
autofrettage conditions and material properties required certain assumptions
in addition to those used in earlier work;   these are described briefly in the
following sections:

2.1.1 Material Properties

The majority of gun steels have tensile properties which are close
to being elastic-perfectly plastic, and in order to avoid the complexities
which arise when strain-hardening is considered such a condition is usually
assumed.   In practice, the strength of the cylinder will tend to exceed that
predicted by using this assumption, and this provides an additional factor of
safety when the gun enters service.

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The 76 mm gun barrel steel used here (see Section 2.5.1) has a
yield/ultimate strength ratio of 0.93, and the use of yield stress as an
effective flow stress is therefore considered justified.

2.1.2 End Conditions

The use of various practical approaches to hydraulic autofrettage
resulted in considerable interest in the effect of end conditions on the
spread of a yielded zone into the cylinder wall.   In addition to theoretical
work [e.g. 7-11], there have been several experimental studies.   For example,
work by Davidson et al [14] showed that predictions based on the open-end
hydraulic autofrettage condition, which is assumed to give rise to no
significant longitudinal stress in the wall, gave the closest agreement with
experimental determinations of the onset of bore yielding.   For swage
autofrettage, however, the local stresses in the barrel wall near the swage
are much more complex and in addition are influenced by the way in which the
cylinder is supported (i.e. pushing the mandrel through while restraining the
cylinder near the swage entry point will produce a different stress
distribution from that involved when the exit point is used to apply the
restraining force).   In the absence of a suitable analysis for the
swage/barrel interface, the open-end condition is assumed.

2.1.3 Yield Criterion

The use of the Tresca yield criterion $\sigma_h - \sigma_r = Y$ has considerable
advantages in that the complexity of the residual stress analysis is greatly
simplified;   the onset of bore yielding, for example, is found to be
independent of cylinder end conditions.   While the implications of using
von Mises' criterion, which gives more accurate predictions of bore yielding
[14], have been discussed by several authors [7,9] it is possible to avoid the
need for additional complexity by using the approximation to von Mises
described by Warren [10] and Hill [9], in which a modified yield stress is
used in Tresca's form of the yield criterion:

$$\sigma_h - \sigma_r = Y^* = 2Y/\sqrt{3}$$

An experimental investigation of the pressures required to produce
full yielding of the wall in open-end cylinders with various wall ratios [14]
suggested that a more appropriate modification to the yield stress is
$Y^* = 1.08Y$, and since this result is supported by the adoption in the UK of a
similar empirical relationship $Y^* = 1.11Y$ for the design of large-calibre gun
barrels [13], the relationship $\sigma_h - \sigma_r = Y^* = 1.08Y$ is used elsewhere in this
report.

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2.2 Elastic Cylinder

Using the notation of Fig. 2, the hoop and radial stresses in a completely elastic cylinder under pressure P are given by the Lamé equations:

$$\sigma_h = P [(b/r)^2 + 1] / (k^2 - 1) \tag{1}$$

$$\sigma_r = -P [(b/r)^2 - 1] / (k^2 - 1) \tag{2}$$

Note that the open-end condition assumed implies that the longitudinal stress $\sigma_z = 0$.

2.3 Elastic-Plastic Cylinder

2.3.1 Yield Radius

As the internal pressure rises, a yield zone spreads from the bore into the wall to a radius r* determined [15] by:

$$P = (Y^*/2) [1 - (r^*/b)^2 + \ln (n^2)] \tag{3}$$

where $n = r^*/a$.

For swage autofrettage, the effective yield interface pressure is not known and it is necessary to estimate the yield ratio n [12,13] from the bore strain e_b, which is defined as the ratio of swage interference to the initial bore diameter. Then [12,13]

$$n^4 \left[\frac{Y^*(1-\nu)}{2Ek^2}\right] + n^2 \left[\frac{Y^*(1+\nu)}{2E}\right] = e_b \tag{4}$$

$$\text{i.e.} \quad n^2 = \frac{-k^2(1+\nu)}{2(1-\nu)} + \left\{\left[\frac{k^2(1+\nu)}{2(1-\nu)}\right]^2 + \frac{2Ee_b k^2}{Y^*(1-\nu)}\right\}^{1/2} \tag{5}$$

This estimate ignores elastic compression of the swage, which is often significant; however, if equation (3) is used to estimate the swage/bore interface pressure, the elastic diametral strain of the swage may be determined from

$$e_{sw} = [P(1-\nu) - \nu\sigma_L] / E_{sw} \tag{6}$$

Where σ_L is the longitudinal compressive stress acting on the swage. From e_{sw} a revised inte·ference, and hence a revised bore strain can be

obtained for further use in equations (5) and (3). Usually, two or three iterations will provide a stable estimate of the interference pressure in equation (3).

The choice of a value for σ_L in equation (6) is difficult without more detailed knowledge of the stresses in the bore; in this instance, assuming that the swaging force is distributed uniformly across the swage face provides an upper limit to the mean longitudinal stress in the swage, and this estimate is used.

2.3.2 Residual Stresses

Considering first the <u>elastic</u> cylinder r* < r < b, which is subjected to a pressure P_1 across the interface at r = r*, then equations (1) and (2) become

$$\sigma_h = P_1 \left[(b/r)^2 + 1 \right] / \left[(b/r^*)^2 - 1 \right] \tag{7}$$

$$\sigma_r = -P_1 \left[(b/r)^2 - 1 \right] / \left[(b/r^*)^2 - 1 \right] \tag{8}$$

At radius r* the yield criterion $\sigma_h - \sigma_r = Y^*$ applies, and hence

$$P_1 = (Y^*/2) \left[1 - (r^*/b)^2 \right] \tag{9}$$

and equations (7) and (8) lead to

$$\sigma_h = \frac{Y^*}{2} \left[\frac{b^2}{r^2} + 1 \right] \left[\frac{r^*}{b} \right]^2 \tag{10}$$

$$\sigma_r = \frac{Y^*}{2} \left[\frac{b^2}{r^2} - 1 \right] \left[\frac{r^*}{b} \right]^2 \tag{11}$$

Considering now a cylinder r < r* < b including a plastic region, then from equation (3) the pressure acting on this cylinder is given by

$$P_2 = \frac{Y^*}{2} \left[1 - \left(\frac{r^*}{b} \right)^2 + \ln \left(\frac{r^*}{r} \right)^2 \right] \tag{12}$$

and as $P_2 = -\sigma_r$ at radius r, then at this radius, again using equation (3)

$$\sigma_r = \frac{Y^*}{2} \left[\left(\frac{r^*}{b} \right)^2 - \ln \left(\frac{r^*}{r} \right)^2 - 1 \right] = -P + Y^* \ln \frac{r}{a} \tag{13}$$

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The yield criterion then leads to

$$\sigma_h = \frac{Y^*}{2}\left[\left(\frac{r^*}{b}\right)^2 - \ln\left(\frac{r^*}{r}\right)^2 + 1\right] = -P + Y^*\left[1 + \ln\frac{r}{a}\right] \qquad (14)$$

To summarize, at autofrettage pressure,

$$\sigma_h = -P + Y^*\left[1 + \ln\frac{r}{a}\right] \qquad\qquad a < r < r^*$$

$$\qquad (15)$$

$$= \frac{Y^*}{2}\left[\left(\frac{b}{r}\right)^2 + 1\right]\left[\frac{r^*}{b}\right]^2 \qquad\qquad r^* < r < b$$

Elastic unloading removes the stresses given in equations (1) and (2), and hence after autofrettage

$$\sigma_{resid} = -P + Y^* \quad 1 + \ln\frac{r}{a} \quad - P\left(\frac{b}{r}\right)^2 + 1 \quad / (k^2 - 1) \qquad a < r < r^*$$

$$\qquad (16)$$

$$= \frac{Y^*}{2}\left[\left(\frac{b}{r}\right)^2 + 1\right]\left[\frac{r^*}{b}\right]^2 - \left[P\left(\frac{b}{r}\right)^2 + 1\right] / (k^2 - 1) \qquad r^* < r < b$$

2.4 Reversed Yielding and the Bauschinger Effect

When the elastic-plastic interface extends far enough into the barrel wall, reversed yielding may occur on unloading; such behaviour would be confined to cylinders with relatively thick walls (b/a exceeding 2.2) if the yield strengths in tension and compression are equal.   However, most gun steels display a reduced compressive yield strength – the Bauschinger effect [16] – which leads to significant reductions in bore residual stress, even in barrels of lightweight, thin-walled design.   The major characteristics of tension-compression stress-strain curves of this type are shown in Fig. 3, which indicates the various parameters which have been used to define the magnitude of the Bauschinger effect; the most popular approach taken has been to use the ratio of compressive yield strength to either the maximum stress in tension [17] or the tensile yield strength [18], but numerous strain and energy parameters such as the strain ratio ϵ_c/ϵ_b [19], Bauschinger Strain ϵ_c [20] and Bauschinger energy parameter E_s [19] have also been proposed.

The limited strain hardening observed in gun steels results in the compressive/tensile yield strength ratio being nearly independent of the amount of the tensile strain, and the ratio is therefore particularly suitable for use here.   However, the use of an elastic-perfectly plastic model for estimation of the stress changes associated with reversed yielding must be regarded as being unsatisfactory, in view of the higher rates of strain hardening observed in compressive loading.   Nevertheless, in order to permit an estimate of the effects of reversed yielding to be obtained, such a model was assumed, with the material yielding in compression at a stress of $-\beta Y^*$,

and sustaining reversed-yield to a radius $\rho*$. While the unloading stress produced by removing the pressure which acts on the bore is estimated in precisely the same way as the original loading stresses, the effective yield stress for reversed yielding is $(1 + \beta)Y*$ instead of $Y*$ [7], and using these conditions for the cylinder $a < r < p*$ in equation (15).

$$\sigma_{unload} = -P + (1 + \beta)Y*\left(1 + \ln\frac{r}{a}\right) \tag{17}$$

Using equation (13) for $p* < r < b$, the pressure acting across the $r = \rho*$ interface is given by

$$P_3 = P - (1 + \beta)\, Y* \ln\frac{\rho}{a} \tag{18}$$

and from equation (1)

$$\sigma_{unload} = \left[P - (1 + \beta)Y* \ln\frac{\rho*}{a}\right]\left[\left(\frac{b}{r}\right)^2 + 1\right] / \left[\left(\frac{b}{\rho*}\right)^2 - 1\right] \tag{19}$$

The net residual stress from equations (15), (17) and (19) is

$$\sigma_{resid} = -\beta Y*\left[1 + \ln\frac{r}{a}\right] \qquad a < r < \rho*$$

$$= Y*\left[1 + \ln\frac{r}{a}\right] - P - \left[P - (1+\beta)Y*\ln\frac{\rho*}{a}\right]\left[\left(\frac{b}{r}\right)^2 + 1\right]\left[\left(\frac{b}{\rho*}\right)^2 - 1\right]$$

$$\rho* < r < r*$$

$$= \left(\frac{Y*}{2}\right)\left[\left(\frac{b}{r}\right)^2 + 1\right]\left[\frac{r*}{b}\right]^2 - \left[P - (1+\beta)Y*\ln\frac{\rho*}{a}\right]\left[\left(\frac{b}{r}\right)^2 + 1\right]\left[\left(\frac{b}{\rho*}\right)^2 - 1\right]$$

$$r* < r < b \tag{20}$$

2.5 Example

2.5.1 Material-Mechanical Properties

This study was associated with a series of swaging trials on forgings for the 76 mm L1A3 gun barrel, and the five barrel sections used were cut from a single forging of 3Ni-1Cr-0.5Mo gun steel, quenched and tempered to a 0.2% proof stress of 1050 MPa, and UTS of 1130 MPa. Charpy V-notch impact tests at -40°C on specimens cut from the ends of the original forging gave values between 20 and 26 J, which would not meet the 26 J specified for the service barrel, but this was not expected to affect any aspects of the autofrettage trial. An elastic modulus of 210 GPa was assumed.

2.5.2 Swaging Procedure

Five test barrel sections approximately 430 mm long were cut from the original forging, and were machined to give interferences between 0.363 and 1.328 mm on a swage of diameter 70.104 mm. Bore and external diameters were measured at three positions along each barrel, in two diametral planes at right angles, to obtain the mean internal and external diameters. Actual bore measurements varied from the appropriate value of mean diameter by ± 0.012 mm (absolute maximum variation being 0.023 mm), a small variation compared with the swage interferences used.

The barrel sections are referred to as A, B, C, D and E, Section A having the smallest swage interference; further dimensions are given in Table I. The wall ratio (ratio of external and internal diameters) was in all cases close to 1.8 and represents a typical value for modern gun barrel forgings.

Each section was given bore coatings of zinc phosphate and 8% Bonderlube (lubricant) prior to heating to 95°C, at which stage the bore was further coated with grease. The swage, heated to 75°C was forced through the barrel, one end of which was located in the loading frame by means of a groove machined in the outside surface. The swage had a shallow lead-in taper, to reduce frictional forces and to assist in maintaining alignment during the swaging operation, but considerable vibration (with an increase in observed swaging force) was observed with barrels A, B and D, indicating break-down of the lubricant. However, it has been reported [21] that such vibration does not have any adverse effects on the results of swaging.

2.5.3 Bauschinger Effect

To estimate the significance of reversed yielding, and to obtain a suitable value for the compressive yield strength of the steel used, a tension-compression stress-strain curve was determined from a threaded-end cylindrical tension specimen (10.13 mm diameter) cut from barrel section A. The orientation of the specimen was chosen to ensure that the hoop tensile properties of the forging were determined and that any hardening effect from local deformation near the bore of the barrel, which was expected to remain

essentially elastic during autofrettage, was avoided.   After a normal tensile
test was performed, using two 12.5 mm gauge-length extensometers mounted at
right angles to each other, the threaded ends of the specimen were machined
off leaving the end faces normal to the axis of the cylinder.   A compression
test was then performed on this cylinder using the same extensometers, and
apart from low-stress differences attributed to initial seating
irregularities, a comparison of the stress-strain records from the two gauges
showed close agreement, confirming that alignment of the specimen and loading
system was satisfactory.   The gauge limits permitted plastic strains of 0.22%
in tension and 0.6% in compression, and the tension-compression curve, shown
in Figure 4, indicates that reversed yielding occurs close to load reversal
for this material.   The difficulties involved in choosing a suitable
criterion for compressive yielding have already been described; in this case,
a plastic strain of 0.05% could be measured reliably, and this criterion was
used in compression.   The value of β was determined to be between 0.40 and
0.43 depending on the choice of tensile stress used for reference (i.e. 0.05%
offset or the maximum tensile stress observed).   A value of β = 0.40 was
adopted for the purpose of calculating residual stresses.

2.5.4 Predicted Residual Stresses in Test Cylinders

Using the procedures described in Sections 2.3.2 and 2.4, the
residual stress distribution was predicted, with and without reversed
yielding, for each of the test barrels; the results are shown in Figure 5,
the significant parameters being listed in Table I.

Several features of the distributions merit further elaboration.

(a)   Ring A was predicted to be completely elastic, as indicated
      in Table I.

(b)   A value of $\rho*/a$ of 1.001 for ring B indicates that reversed
      yielding is just starting at the bore.

(c)   The residual compressive stress at the bore surface is independent
      of the level of autofrettage, once reversed yielding occurs.   The
      effect of increased swage interference is to promote the spread of a
      zone of material at approximately constant residual stress level
      into the barrel wall, this behaviour following from equations (16)
      and (20), which indicate that at the bore (r = a)

$$\sigma_{resid} = Y* - 2Pk^2/(k^2-1) \quad \text{(no reversed yielding)} \tag{21}$$

$$\sigma_{resid} = -\beta Y* \qquad \text{(with reversed yielding)} \tag{22}$$

      The residual stress at the bore increases linearly with pressure
      (equation (21)) until reversed yielding occurs at the bore surface,
      when from equations (21) and (22),

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$$P = (1 + \beta) \, Y^* \, (k^2 - 1) \, / \, (2k^2) \qquad\qquad (23)$$

which is consistent with the use of a yield stress of $(1 + \beta) \, Y^*$ and $(p^*/a) = 1$ in equation (3). After this, from equation (22), the residual stress remains constant, as a result of which the effectiveness of additional swaging in reducing the growth rate of cracks immediately next to the bore surface is therefore questionable. For deeper cracks, however, the effect of larger swage interferences is still beneficial, in that the compressive stress would act over a greater proportion of the crack length.

(d) The significance of the parameter β in the above effect is clear; the residual compressive bore stress after autofrettage would be expected to be proportional to β in barrels in which reversed yielding occurs. However, the appropriateness of the elastic-perfectly plastic model of material behaviour which has been assumed is in some doubt; in practice, deviations from linearity are observed soon after compressive loading begins (Figure 4), and the reversed-yield zone should therefore behave as a composite of materials whose properties vary from $\beta = 0$ at the maximum extent of the reversed-yield zone to $\beta \sim 1$ where significant reversed plasticity has occurred, necessarily near the bore. Any model incorporating such behaviour is extremely complex, and all that can be stated is that in practice the contribution of reversed yielding to the barrel stresses is likely to lead to a reduction in the level of compressive residual stress, the reduction being a maximum near the bore and decaying to zero at the original (monotonic) yield radius r*. This differs considerably from the behaviour predicted in Figure 4, and in view of the significance of reversed yielding in determining the near-bore residual stress, clearly requires further investigation.

(e) Increasing the level of autofrettage beyond that required to extend the yield zone to approximately mid-wall thickness produces little benefit in terms of changes to the residual stress distribution. In fact, the major effect of any such increase is to raise the tensile hoop stress acting at the exterior wall of the barrel, but as this reduces the critical crack length for external cracks, excessive autofrettage must be regarded as being undesirable. The optimum level is clearly that which produces equal fatigue lives for cracks growing from bore and exterior wall.

3. EXPERIMENTAL RESIDUAL STRESS DETERMINATION

3.1 X-Ray Residual Stress Measurement

The tangential component of the residual stress in each barrel was measured on ring specimens, (25 mm thick) cut from the central part of the barrel. Two techniques were used; initially a multi-exposure film technique [23], based on measuring the position of the 211 martensitic back reflection (at a 2θ value of approximately 156°) relative to a 222 reflection from

stress-free silver powder, was used with chromium radiation. Results were satisfactory, but the inconvenience of long exposure times prompted the use of a multi-exposure diffractometer technique [22]. Chromium radiation was again used in this case, as the use of a 310 reflection with cobalt radiation which would have provided greater penetration of the surface, produced a poor line to background ratio. Attempts to use copper radiation were completely unsatisfactory, as fluorescence from the iron specimen gave unacceptably high background radiation levels. Output from the diffractometer was digitized and collected on paper tape; after readings were completed, peak analysis was carried out using a PDP-10 computer. Despite the reduced exposure times obtained with this technique, the need to use a small (1 mm) spot size because of the high stress gradients across the specimen still resulted in total reading times which limited the number of measurements possible on each specimen.

3.2 Surface Preparation

The limited penetration of the surface achievable with chromium radiation added considerably to the difficulties which are usually encountered when using X-rays to measure residual stresses in high-strength steels, and particular care had to be taken with surface preparation; many measurements were made in the course of evaluating the various polishing techniques available. The surface preparation finally used consisted of the following:

(a)   Bandsaw ring from barrel.

(b)   Grind ring face, removing minimum of 2 mm.

(c)   Finish grinding by reducing cuts gradually, the last cuts being made by elastically loading the grinding head.

(d)   Hand polish a radial strip at least 6 mm wide with waxed SiC paper (grade 1200).

(e)   Hand polish with 4-8 m diamond paste.

(f)   Electropolish strip using a fresh glacial acetic acid: chromium trioxide:water (133 ml : 25 g : 7 ml) solution and an aluminium alloy cathode 6 mm from the ring surface; the remainder of the specimen was masked with wax. Polishing conditions were as follows: 12°C, 15V for approximately 25 mins, with continuous agitation.

Measurements of the residual stress in ring A, which was expected to be zero, showed a distribution around zero $\pm$ 40 MPa, which was judged to be adequate.

3.3 Results and Discussion

Figure 6 shows the predicted and measured residual stress distributions for each barrel. With one exception, agreement between the two distributions is good, considering the limited number of experimental data points. More specifically, the influence of the Bauschinger effect in reducing residual bore compression is clearly confirmed; the measured bore stresses are considerably below those which are predicted (Figure 5) when the effect of reversed yielding is omitted. Resolution near the bore is not sufficiently good to make an assessment of the detailed distribution produced by reversed yielding, but it is clear that the use of the predicted curve in a crack growth rate prediction model would not lead to major errors.

The exception referred to above is the distribution in Ring E, in which measured residual stresses near the bore are consistently higher than those predicted. While it is possible for the residual stress distribution along any one radius to be completely positive, such behaviour cannot occur on all radii, and the appearance of a residual stress distribution which was predominantly positive suggested that the stresses in this barrel were not symmetrical around the bore. To investigate this effect further, another ring was cut from barrel E and radial strips were prepared for X-ray residual stress measurement at 45° intervals around the bore. The residual hoop stress distributions measured are shown in Figure 7, and these were used to construct a series of residual stress contours which could be superimposed on the barrel section as shown in Figure 8. It is clear that deformation of the barrel during swaging was not uniform. This behaviour is not entirely unexpected; the behaviour of the material in tension is close to elastic-perfectly plastic, and a feature of such behaviour in autofrettage is that after yielding occurs at any point on the barrel exterior, deformation would be expected to continue quite freely at that point, producing asymmetric distortion of the section. While the (limited) strain hardening properties of the real material will tend to maintain a more axisymmetric deformation pattern, it is clear that swaging barrels in which yielding extends completely through the wall represents a much less stable autofrettage system than one in which the yield zone is limited to the bore region. In view of the negligible benefits associated with autofrettage at high strains, as described in Section 2.5.4, and the disadvantages of high tensile residual stresses produced at the exterior wall, swaging of barrels to full wall thickness yield appears to be inadvisable.

The effects of autofrettage residual stresses on fatigue crack growth rate is the subject of another report.

4. CONCLUSION

The residual hoop stress distributions predicted for swage autofrettage of 76 mm gun barrel forgings were found to be in good agreement with residual stresses determined using an X-ray measurement technique, except where yielding of the whole barrel wall thickness occurs in which case non-axisymmetric deformation occurs and the residual hoop stress varies considerably around the barrel wall.

Since the use of high levels of autofrettage produces little benefit in terms of increased residual compressive stress, and may reduce barrel life by promoting rapid fracture of the barrel from fatigue cracks which initiate at the outer wall, the use of swage autofrettage using interferences greater than that required to promote yielding to approximately mid-wall thickness is not recommended.

5. ACKNOWLEDGEMENTS

6. REFERENCES

1. Robertson, F.L., "The Evolution of Naval Armament", 1921.

2. Jacob, L. Mem. Artillerie, 1, 138 (1907).

3. Davidson, T.E., Throop, J.F., Austin, B.A. and Reiner, A.N.,
    "Analysis of the Effect of Autofrettage on the Fatigue Life
    Characteristics of the 175 mm M113 Gun Tube", Report WVT-6901,
    Watervliet Arsenal (1969).

4. Nishioka, K. and Hirakawa, K., "Effect of Internal Surface Flaw
    on the Fatigue Strength of a Thick Walled Cylinder under Cyclic
    Internal Pressure", Proc. 2nd Intl. Conf. High Pressure Engng.,
    Brighton, July 1975, I. Mech. E. (1977).

5. Clark, G., "A High Sensitivity Potential-Drop Technique for
    Fatigue Crack Growth Measurements", Report MRL-R-755, Materials
    Research Laboratories (1979).

6. Clark, G., "Use of Weight Functions to Determine the Stress Intensity
    for a Cracked Thick Walled Cylinder", Report MRL-R-814, Materials
    Research Laboratories (1981).

7. Prager, W. and Hodge, P.G. Jr., "Theory of Perfectly Plastic
    Solids", Wiley (1951).

8. Nadai, A., "Theory of Flow and Fracture of Solids", McGraw-Hill (1950).

9. Hill, R., "The Mathematical Theory of Plasticity", Oxford University
    Press (1950).

10. Warren, A.G., "Autofrettage", Proc. Symp. Internal Stresses in Metals
    and Alloys, p. 209-218, Inst. of Metals (1947).

11. Macrae, A.E., "Overstrain of Metals", H.M.S.O. (1930).

12. Almond, W.C., "The Design of Autofrettaged Gun Barrels", Tech.
     Report 36/64, Ministry of Supply, U.K. (Armament Design Department)
     (1944).

13. Moss, L.T.J., "The Design of Gun Barrels, A Description of the Working
     Method", Memorandum (P)43/58, Armament Research and Development
     Dept., Ministry of Supply (U.K.) (1958).

14. Davidson, T.E., Barton, C.S., Reiner, A.N. and Kendall, D.P.
     "Overstrain of High-Strength Open-End Cylinders of Intermediate
     Diameter Ratio", Proc. 1st Intl. Congress Exp. Mechanics, Dec. 1961.

15. Turner, L.B., Trans. Camb. Phil. Soc. 21, 377 (1909).

16. Bauschinger, J., Civilingenieur, 27, 289 (1881).

17. Milligan, R.V., Koo, W.H. and Davidson, T.H., "The Bauschinger Effect
     in a High Strength Steel", J. Basic Engng., 88(D), 480-488 (1966).

18. Welter, G., "Micro- and Macro-Deformations of Metals and Alloys Under
     Longitudinal Impact Loads", Metallurgica, Part I, 287-292, Part II,
     328-330, Part II, 13-17 (1948).

19. Abel, A. and Muir, H., "The Bauschinger Effect and Discontinuous
     Yielding, Phil. Mag., 26, 489-504 (1972).

20. Buckley, S.W. and Entwistle, K.M., "The Bauschinger Effect in Super-
     Pure Aluminium Single Crystals and Polycrystals", Acta Metallurgica
     4, No. 4, 352-361 (1956).

21. Davidson, T.E., Barton, C.S., Reiner, A.N. and Kendall, D.P.
     "A New Approach to the Autofrettage of High Strength Gun Tubes", IPM
     Project Report, Watervliet Arsenal, April 1959.

22. Clark, G. and Tate, G.R., "The Residual Stress in Gun Barrels",
     Presented at 4th Australian Natl. Conf. on X-ray Analysis,
     Canberra, February 1980.

23. Hawkes, G.A., "The Measurement of Surface Residual Stress by X-Rays",
     Brit. Jnl. Appl. Physics, 8, 229-232 (1957).

TABLE I

SPECIMEN DETAILS, AND PREDICTED

AUTOFRETTAGE BEHAVIOUR

	A	B	C	D	E	
Bore Diameter, mm	69.741	69.499	69.256	69.007	68.776	
Swage Interference, mm on diameter	0.363	0.605	0.848	1.097	1.328	
k = od/id	1.7944	1.8000	1.8055	1.8127	1.8206	Measured
Max. Swage Force (Tonnes)	27.5	35.4	33.4	43.2	45.2	
Residual Bore Expansion (mm)	0.035	0.160	0.360	0.590	0.750	
Residual Bore Expansion (mm)	0.000	0.090	0.260	0.480	0.700	
Radial Swage Pressure (MPa)	381	550	628	665	679	Predicted
Monotonic Yield Radius r*/a	Elastic	1.257	1.468	1.650	1.793	
Reversed Yield Radius ρ*/a	Elastic	1.001	1.075	1.113	1.127	
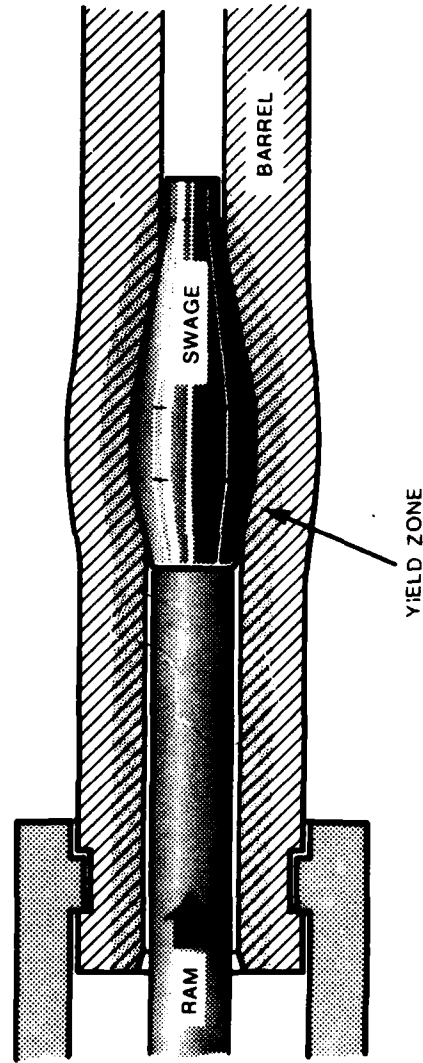
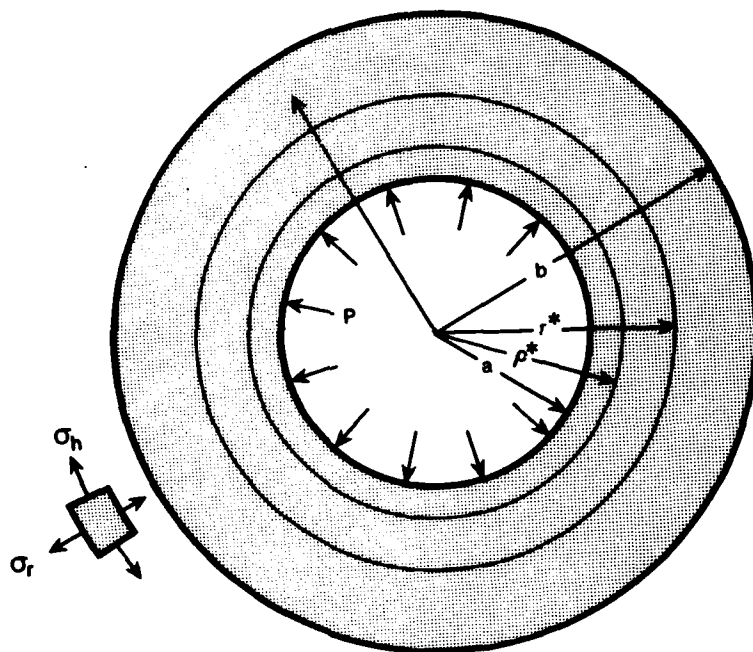Fig. 1.   Schematic representation of push-swage autofrettage.

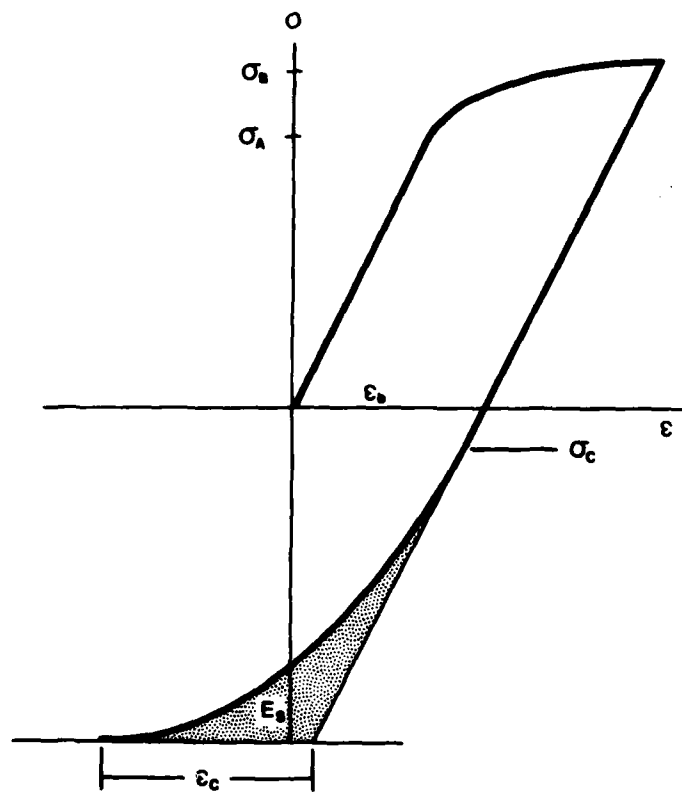Fig. 2.   Barrel Section, showing monotonic and reversed yield zones.

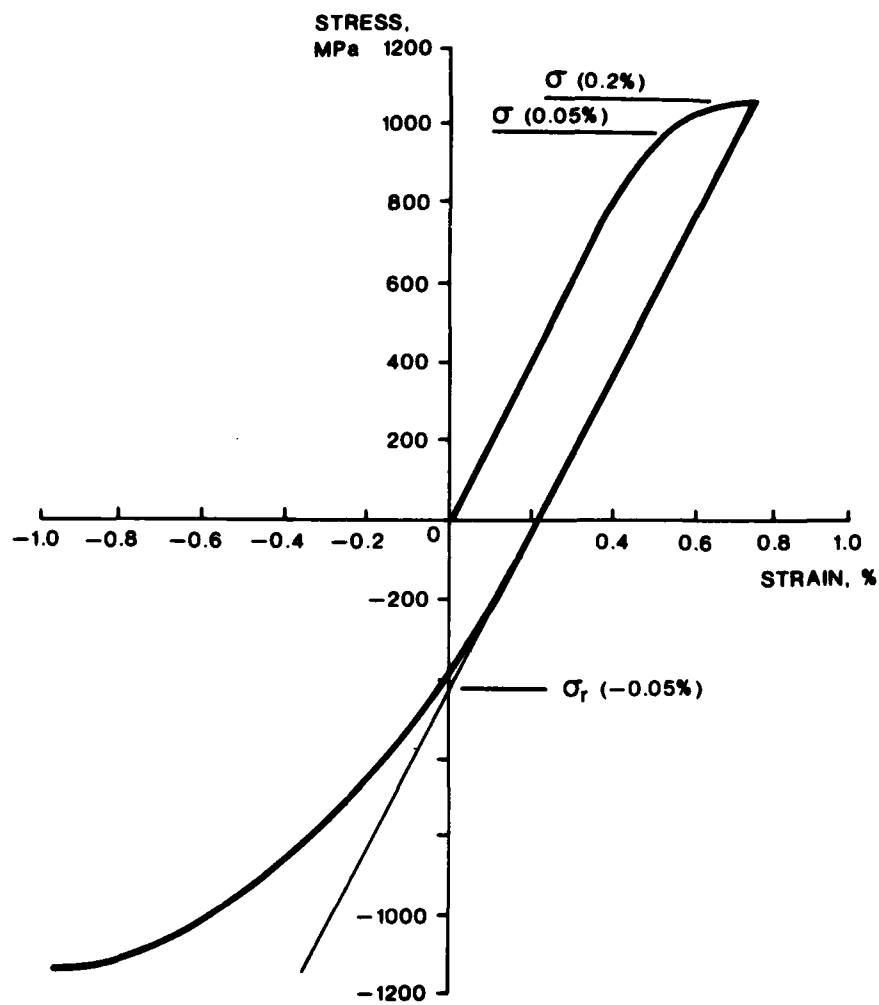Fig. 3.   Bauschinger effect parameters (schematic)

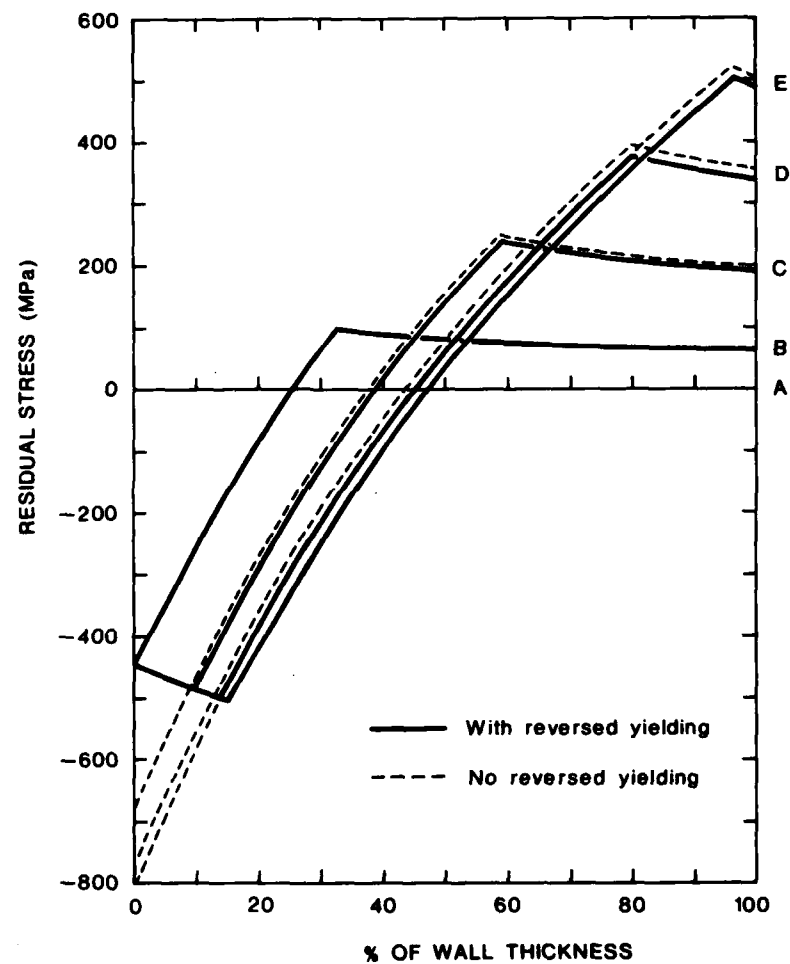Fig. 4. Tension-compression stress-strain properties of gun steel.

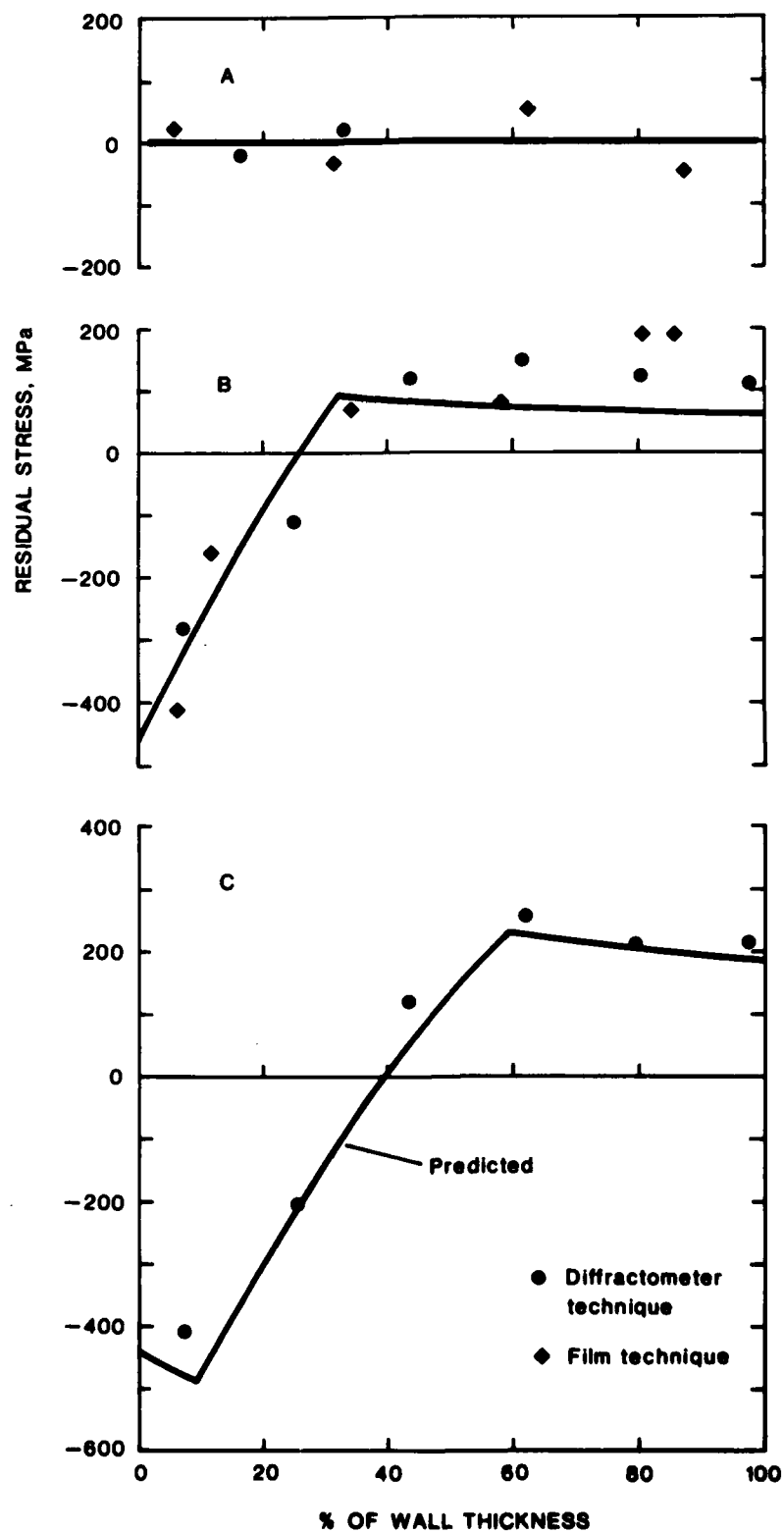Fig. 5. Predicted residual stress distributions for barrel sections B to E.

Y-axis label: RESIDUAL STRESS, MPa

X-axis label: % OF WALL THICKNESS

Legend:
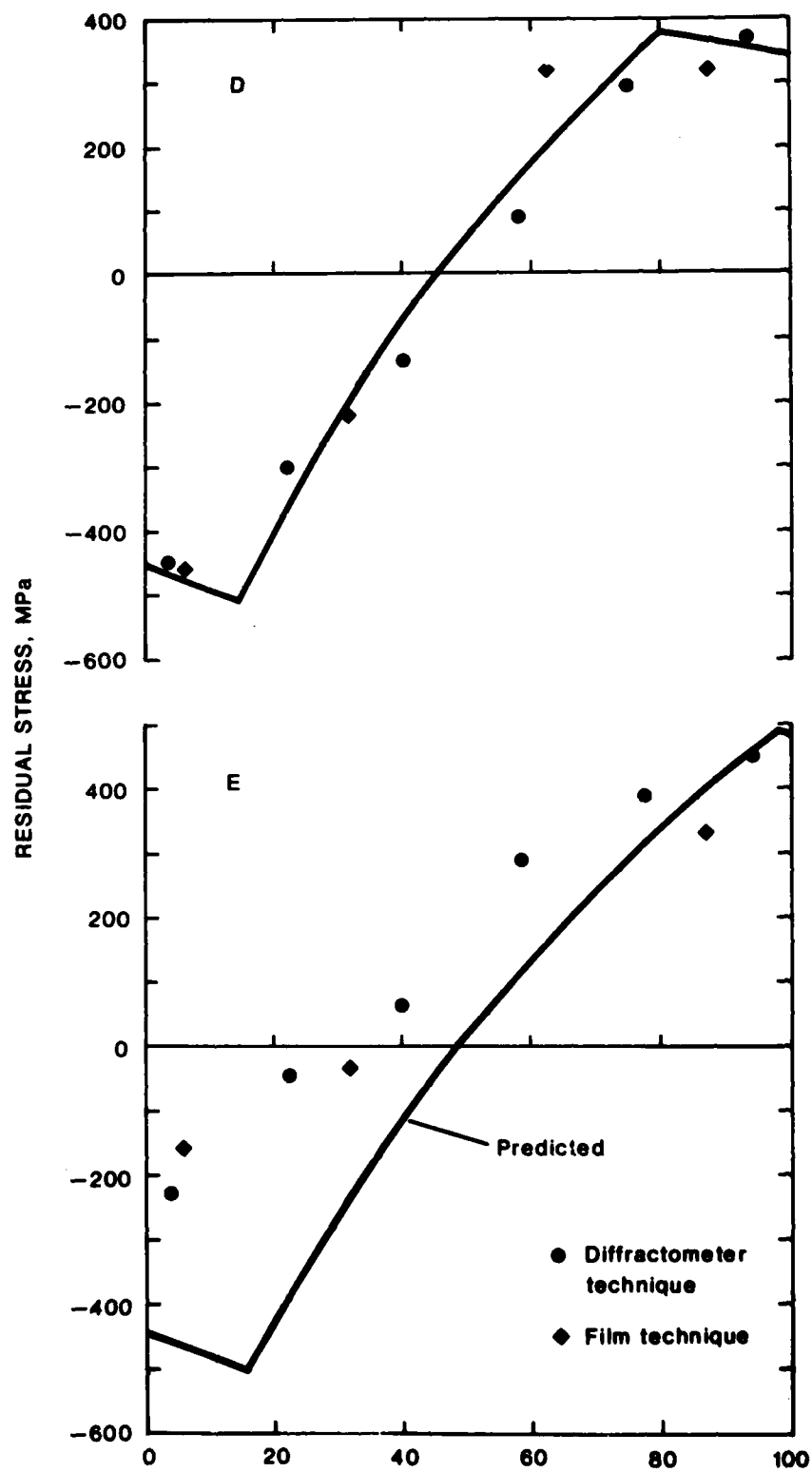● Diffractometer technique
◆ Film technique

Predicted

Fig. 6. Measured residual hoop stresses in barrel sections A to E. Predicted distribution (assuming reversed yielding) is indicated.

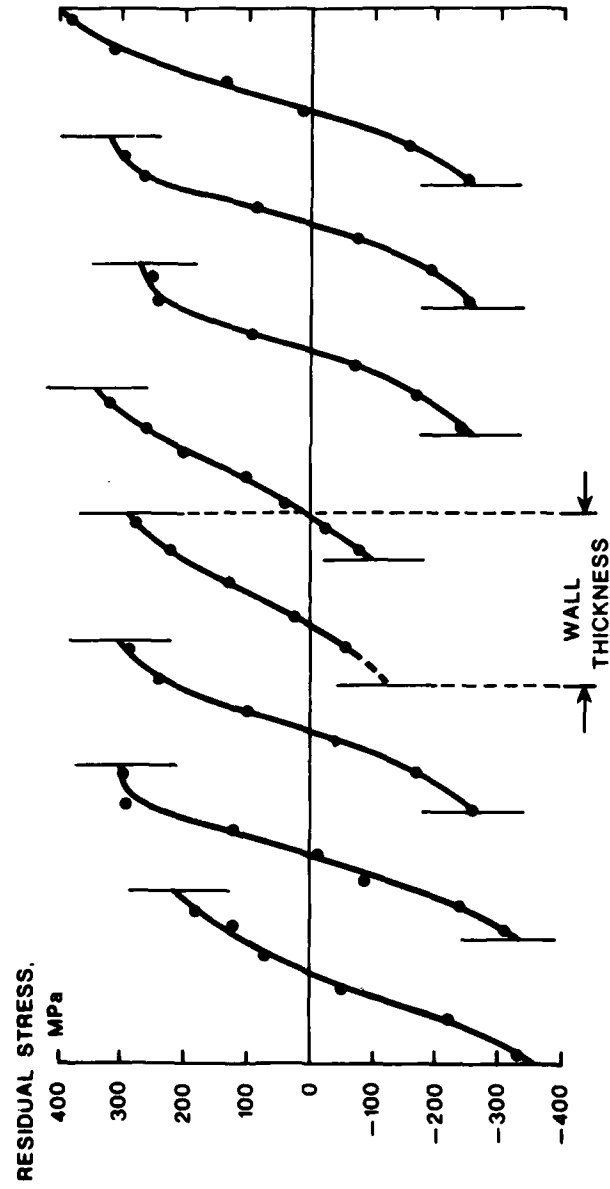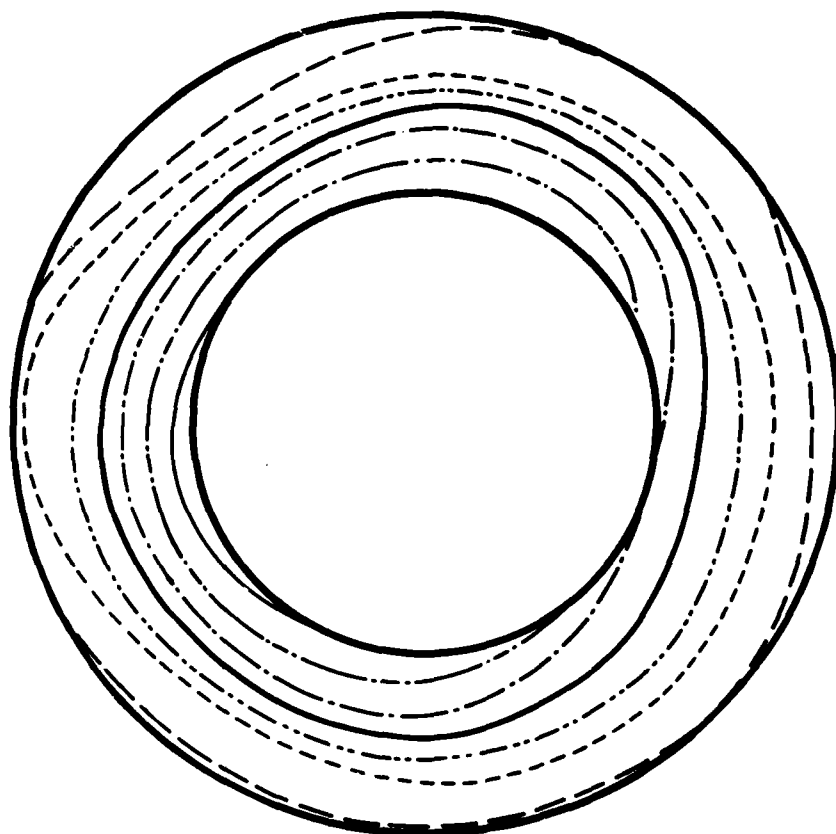Fig. 7. Residual hoop stress measured on eight radial lines (45° apart) on a ring from barrel section E.

RESIDUAL HOOP STRESS

Contour	MPa
— — — —	300
— — — — —	200
—··—··—	100
——————	0
—·—·—·—	−100
—··—··—	−200
——————	−300

Fig. 8. Distribution of residual hoop stress in a section of barrel E, derived from Fig. 7.

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